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Computational Data Compression for Effective Storage/Retrieval

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ABSTRACT

As the use of networked computers continued its growth and storage devices became smaller, faster and affordable, the need for efficient and rapid storage and retrieval of material data has increased considerably. In this paper, a powerful computational tool known as the Multi-Factor Interaction Model (MFIM) is used to compress material test data and efficiently store and retrieve these data. The process of data compression and retrieval is demonstrated for high temperature alloy modulus, yield and ultimate strength, 1000 hours rupture strength, thermal expansion coefficient, and thermal conductivity. MFIM can be used to predict material behavior when little data is available and can account for single or multiple effects on the material response. This is demonstrated with an example showing the combined effect of temperature and stress in predicting the time dependent rupture strength of a high temperature alloy.

INTRODUCTION

The technological achievements made last century have been tremendous. Major advances were made in computational technology where networked computers have become affordable, faster, and smaller. Simultaneously, improvements in the area of material development have been pressing on where government, industry, and academia are supporting the development of advanced materials and manufacturing processes that conform to the principle of "better, faster, and cheaper" with enhanced safety and reliability. The durability of a developed material is established through costly testing to ensure that it possess the strength and other properties that are required in the design. In addition, development of material for a specific field of application may require certification. Any changes in the manufacturing process or the material chemistry may require a repeat of some or all the tests taken earlier. Therefore it is very evident that in the field of material development, engineers are forced to work with substantial amounts of data, which are normally stored in tables or graphs. The challenge is even greater when one desires to rapidly retrieve and use the collected data to extrapolate or predict behavior at conditions that are not available in the test data.

Generally, effective usage of collected test data requires extensive numerical interpolation or extrapolation and modeling. For example, to quantify the effect of temperature with respect to mechanical properties increased or decreased temperature testing is required. The material property obtained from the test will likely not cover all temperature regimes and usually is done in large temperature increments to reduce the cost of the experiment. This concept is illustrated in the data shown in table 1 where test data obtained for the modulus, yield strength, and rupture strength of several alloys are listed. These test data are obtained from a variety of handbooks, which requires extensive time to collect. Working through congested data sheets to properly predict the property at the desired condition could lead to erroneous material selection. Difficulty further emerges when one attempts to estimate the effect of other physical conditions on the considered property. This paper demonstrates that there exists a unique and a powerful computational tool named the Multi-Factor Interaction Model (MFIM) (ref. 1) which can be used in conjunction with a well established procedure for the (1) rapid storage and retrieval of test data, (2) prediction of material property at conditions beyond what is collected in a specific test, and (3) assessment of one or multiple effects without resorting to costly and lengthy experimental testing.

THE MULTI-FACTOR INTERACTION MODEL (MFIM)

MFIM is depicted in detail in figure 1. As shown in the figure, the following effects are included in the MFIM: temperature, stress, creep, mechanical cycling, thermal cycling, and frequency. These effects can be evaluated individually or collectively. MFIM is novel because it permits its user to add additional effects as deemed necessary. It is a "virtual laboratory" because it permits a quick assessment of the property at hand subject to various conditions and effects. For example, to evaluate the effect of temperature on the material property, one needs to identify the following: T_m (material melting temperature), M_{p0} (material property at reference condition), and the exponent h. Once these factors are identified, one can instantaneously estimate the material property at any desired temperature. The exponent h is usually determined through a calibration process as it is detailed in section 4 of this paper.

It is worth noting that MFIM will predict behavior or properties in applications beyond regimes where data can be extrapolated or interpolated and where complex interactions must be considered the area of estimating material properties. Professionals who work with aircraft data, forecast data, instrumentation and measurement data, satellite data, financial data, pharmaceutical data, and medical data can benefit from the use of MFIM in their respective applications. This can be done through the suitable equivalency of the physical parameters shown in MFIM in figure 1 to those of the application at hand.

PROCEDURE FOR DATA COMPRESSION AND RAPID RETRIEVAL

The process of data compression and rapid retrieval is summarized in the flow chart presented in figure 2. The first step is to select the parameter of interest (such as material property) and the effect on the parameter of interest that is to be evaluated (such as temperature). The second step is to identify the parameter of interest reference value (reference material property) and the limit of the selected effect (such material melting temperature). The third step is to collect and store the available test data (such as temperature dependent properties). Once all the relevant parameters and limits have been identified and the test data have been collected, the process of calibration begins to determine the proper MFIM exponent that provides a good match of predicted MFIM properties against those collected from the experiment. The retrieval process is detailed in figure 2. The process begins by selecting a parameter of interest and selecting its correspondent effect(s). The conditions needed for response evaluation are then identified. The next step is to extract the exponent(s) for the selected conditions. A simple program can then be used to evaluate the parameter via MFIM at the selected conditions and print a report to the user. The storage and retrieval of material properties using MFIM is depicted in figure 3 in the three dimensional array that includes property of a material, factor (effect), and exponent for the range of the effect. The procedure with the array can be implemented for in-service prognostics.

An example of MFIM is shown in the next two sections for predicting the properties of nickel alloy used in high temperature application. It is very important to recognize that MFIM can be easily applied to predict and assess the effect of temperature, stress, time, mechanical cycling, thermal cycling, frequency, environment, and many others on the properties of composite materials as well as metals.

MFIM ESTIMATION OF NICKEL ALLOY MECHANICAL PROPERTIES

The MFIM exponent calibration process is illustrated here through the estimation of temperature dependent modulus for a high temperature alloy as shown in figure 4. Test data are available for the modulus starting from the reference temperature and in large temperature increments up to about 75% of the melting temperature. The temperature dependent modulus is computed by evaluating $M_{P0}[1 - T/T_m]^h$. A dedicated computer algorithm is then called to read the available test data and to compute the modulus at the temperatures identified in the test data. The computer code keeps modifying the exponent until the difference between the modulus from the test and the one estimated using MFIM is less than a specified tolerance level. Note that this convergence criterion is evaluated for all available test points. As shown in figure 4, MFIM predicted the degradation in the modulus with great accuracy by using an exponent of 0.22. One additional benefit of MFIM is that it can be used to predict the property outside the upper and lower bounds of the collected data points.

If MFIM convergence is not achieved for a particular effect, the range of the effect is divided into sub-ranges. Then one exponent is used for each sub-range to ensure convergence. That is shown in figure 5 where two exponents are needed to assess the effect of temperature on the yield strength. The ratio of yield strength over the yield strength at reference temperature is plotted versus the ratio of actual temperature to the melting temperature (T/T_m). For the yield strength, a bimodal form of MFIM is needed to predict the temperature dependent yield strength. In this case two exponents are required: -0.135 and 0.475. When T/Tm is less than 0.5, the exponent –0.135 is used. When T/Tm is larger than 0.5, the exponent 0.475 is used. Note that the faster the drop in the data, the larger the exponent. Other strength properties are also estimated using MFIM. The plot presented in figure 6 shows the effect of temperature on the ultimate strength. Again, MFIM needed two exponents to accurately predict the degradation in the ultimate strength. An exponent of –0.145 is needed for a T/Tm less than 0.5 and an exponent of 0.21 is needed for the remaining temperature range.

In addition to predicting the modulus and strength, MFIM is used to estimate the change in the tensile elongation under temperature load. The ratio of the temperature dependent tensile elongation to tensile elongation at room temperature is plotted in figure 7. Note that the tensile elongation is again predicted using a bimodal form of MFIM where two exponents are needed: 0.135 from room temperature up to a temperature ratio of 0.6 and an exponent of –0.125 for the remaining temperature range. Note that the tensile elongation decreases quickly with temperature but increases rapidly as soon as the temperature ratio reaches 0.6. The temperature ratio of 0.6 might correspond to a transition temperature beyond which the material softens. It is evident that depending on the material property and depending on the effect range, single or multiple exponents might be needed for use in MFIM although most properties can be estimated with a single exponent.

As mentioned earlier, MFIM can be used to account for multiple effects on the material property. This capability is demonstrated here by evaluating the combined effect of temperature and static stress on the nickel alloy 1000 hours rupture strength. The results presented in figure 8 show that for a sustained stress ratio of 70% of the static strength, the 1000 hours rupture strength varies significantly with temperature. The higher the temperature, the lower the rupture strength, which is evaluated as a function of time (varying from zero hour to 1000 hours). Also, it is worth noting that the higher the sustained stress to static strength ratio, the faster the drop in the rupture strength. MFIM that is used in this particular evaluation is $[1 - T/T_m]^h[1-\sigma t/S_f t_f]^n$ where σ/S_f is the sustained static stress to ambient-conditions static strength ratio and t/t_f is the ratio of actual time to final time. For the rupture strength results presented in figure 8, the selected temperature and stress effects exponents are respectively 0.38 and 0.5. At temperature ratios of 0.63 and 0.72, the available test data for the 1000 hours rupture strength match those that are estimated by MFIM. This particular application shows the uniqueness and power of the MFIM of predicting material behavior when few data points are available. One can imagine the cost and time involved in running experiments for various stress to strength ratios as a function of time and temperature. Although the MFIM results presented in figure 8 pertain to assessing the time dependent rupture strength at a constant stress level, the work can be readily re-evaluated at other stress levels. It is important to realize that the use application of MFIM is not limited to mechanical properties but as shown in the next section, it is efficient in evaluating thermal properties as well.

MFIM ESTIMATION OF NICKEL ALLOY THERMAL PROPERTIES

MFIM can be equally applied to the prediction the thermal properties of any material. The effect of temperature on the thermal expansion coefficient of nickel alloy is assessed and presented in figure 9. Note that the thermal expansion coefficient is an important variable needed for computing thermal stresses. As shown in the plot in figure 9, MFIM estimated very well the temperature dependent thermal expansion coefficient using an exponent of –0.3. MFIM is also used in evaluating the effect of temperature on the thermal conductivity (exponent –0.485) as shown in figure 10. The thermal conductivity is an essential property that is needed for thermal analysis. The rate of change is faster in the case of the thermal conductivity than that of the thermal expansion coefficient. Note that for both properties, the prediction of MFIM matches the experimental data and permits accurate evaluation at any temperature, even at conditions beyond those of the experiment.

COMPRESSION AND RAPID RETRIEVAL OF NICKEL ALLOY PROPERTIES

The results presented in figures 4 through 10 illustrate the calibration of exponents for usage in MFIM to predict the thermo–mechanical material properties. The effect of temperature on the modulus, strength, tensile elongation, thermal expansion coefficient, and thermal conductivity can be evaluated at any temperature level by plugging the reference property, temperature ratio, and exponent in $M_{p0}[1-T/T_m]^h$. As for the 1000 hours rupture strength, the coupled effect of temperature and stress at various time increments is determined by evaluating the combined two factors $[1 - T/T_m]^h[1-\sigma t/S_f t_f]^n$. Table 2 shows that the results presented and discussed in this paper can be conclusively summarized and compressed using MFIM. Hundreds of test data points that pertain to material property subject to single or multiple effects, can be easily compressed (reduced to a single equation) for rapid retrieval and can be instantaneously evaluated. Upon request, MFIM can be called along with the reference property and limits and can estimate the material property for any range of the selected effect(s). This is surely a unique and powerful approach for efficient data storage and rapid retrieval.

CONCLUSION

This paper introduced and described the Multi-Factor Interaction Model MFIM in details. It is an innovative computational approach that can be used to compress large amounts of data and efficiently use these data for rapid evaluation of material property. MFIM was shown to successfully account for single or multiple effects on the response of interest. Some specific conclusions are listed here: (1) MFIM predicted with excellent accuracy the effect of temperature on the thermo-mechanical properties of nickel alloy, (2) MFIM estimated the nickel alloy 1000 hours rupture strength subject to temperature and time effects at constant stress level, and (3) the process of data compression and retrieval is demonstrated for the thermo-mechanical properties and rupture strength. It is asserted that the proposed computational simulation is an effective approach to predicting the behavior of materials without immediate resort to lengthy and costly experiments.

REFERENCES

1. C.C. Chamis and L. Minnetyan, "A Multi-Factor Interaction Model (MFIM) for Damage Initiation and Progression," Proceedings of the 2001 ASME Winter Annual Meeting, New York City, November 2001.

Table 1. Temperature Dependent Alloys Mechanical Properties
(T/Tm= Temperature/Melting Temperature, Mp / Mp0 = Property/Reference Property)

Alloy 1, Material Property: Elastic Modulus											
T / T_m	0.03	0.08	0.16	0.24	0.32	0.40	0.48	0.56	0.64	0.72	0.80
M_p / M_{p0}	1.000	0.983	0.956	0.926	0.899	0.866	0.832	0.795	0.758	0.728	0.708
Alloy 2, Material Property: Elastic Modulus											
T / T_m	0.03	0.08	0.16	0.24	0.32	0.40	0.48	0.56	0.64	0.72	0.80
M_p / M_{p0}	1.000	0.977	0.937	0.897	0.857	0.821	0.781	0.741	0.694	0.651	0.591
Alloy 3, Material Property: Elastic Modulus											
T / T_m	0.03	0.08	0.16	0.24	0.32	0.40	0.48	0.56	0.64	0.72	0.80
M_p / M_{p0}	1.000	0.972	0.945	0.914	0.881	0.844	0.804	0.755	0.700	0.636	0.538
Alloy 4, Material Property: Yield Strength											
T / T_m	0.03	0.42	0.50	0.58	0.67	0.75	0.83				
M_p / M_{p0}	1.000	0.538	0.450	0.388	0.325	0.250	0.200				
Alloy 5, Material Property: 1000 hr Rupture Strength											
T / T_m	0.48	0.52	0.56	0.60	0.64	0.68	0.72	0.76	0.80	0.84	0.88
M_p / M_{p0}	1.000	0.885	0.808	0.692	0.615	0.538	0.462	0.385	0.327	0.288	0.231

Table 2. MFIM Compression of Test Properties for Rapid Retrieval

Property	Effect	Exponent	Application Range
Modulus	Temperature	0.22	all temperatures
Yield Strength	Temperature	(-0.135) and 0.475	0.475 for T/Tm > 0.5
Ultimate Strength	Temperature	(-0.145) and 0.21	0.21 for T/Tm > 0.6
Tensile Elongation	Temperature	0.135 and (-0.125)	(-0.125) for T/Tm > 0.6
1000 Hr Rupture Strength	Temp.,Time, & Stress	0.38 and 0.5	0.38 for Temp, 0.5 for Time
Thermal Expansion Coeff.	Temperature	(-0.3)	all temperatures
Thermal Conductivity	Temperature	(-0.485)	all temperatures

$$\frac{M_{p\sigma}}{M_{po}} = \left(1 - \frac{T}{T_m}\right)^h \left(1 - \frac{\sigma}{S_f}\right)^n \left(1 - \frac{\sigma t}{S_f t_f}\right)^q \left(1 - \frac{\sigma_m N_m}{S_f N_{fM}}\right)^r \left(1 - \frac{\sigma_T N_T}{S_f N_{fT}}\right)^u \left(1 - \frac{\sigma \omega}{S_f \omega_f}\right)^v \ldots$$

Where:

M_p : material property (mechanical, thermal, physical, etc.)
T : temperature
S : strength
σ : stress
N : number of cycles
t : time
ω : frequency
… : other effects as needed

Subscripts:

m : phase transition
o : reference condition
f : final condition
M : mechanical load
T : thermal cyclic load

Figure 1. The Multi-Factor Interaction Model MFIM

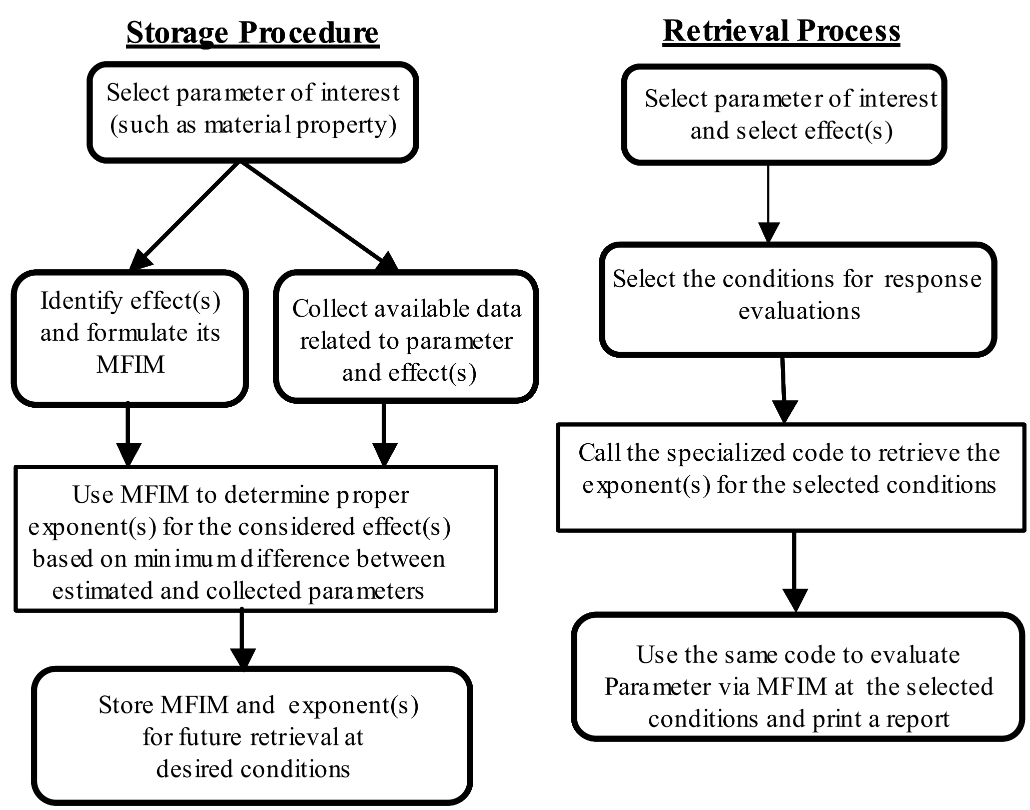

Figure 2. Flow Chart for Data Compression and Rapid Retrieval Methodology

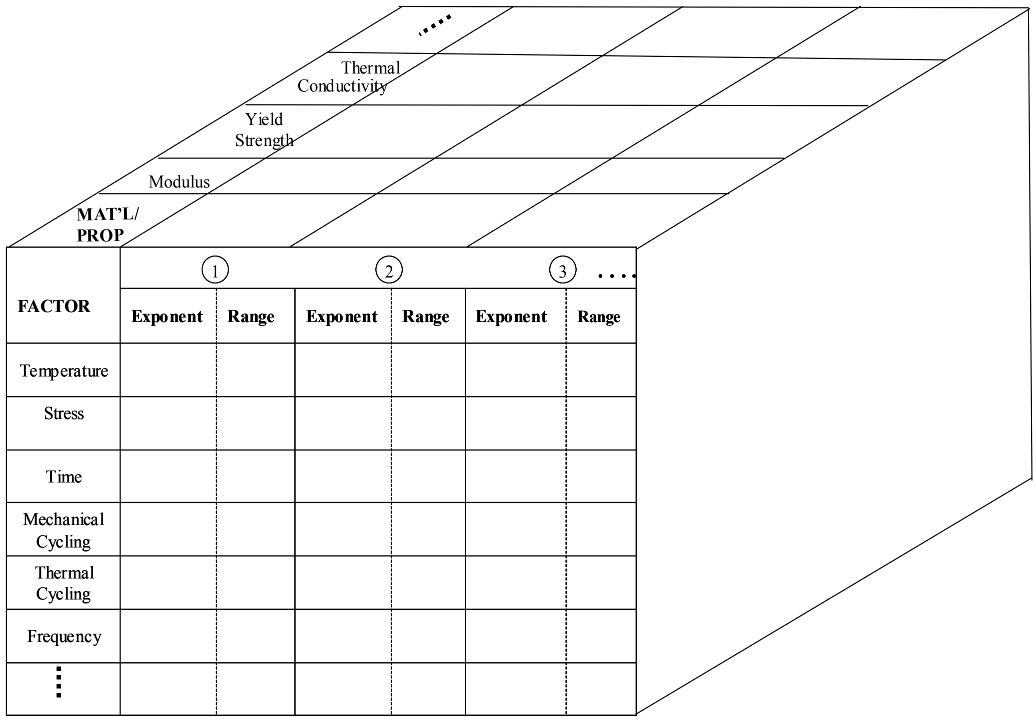

Figure 3. Three Dimensional Array For MFIM Material Property Compression Storage/Retrieval

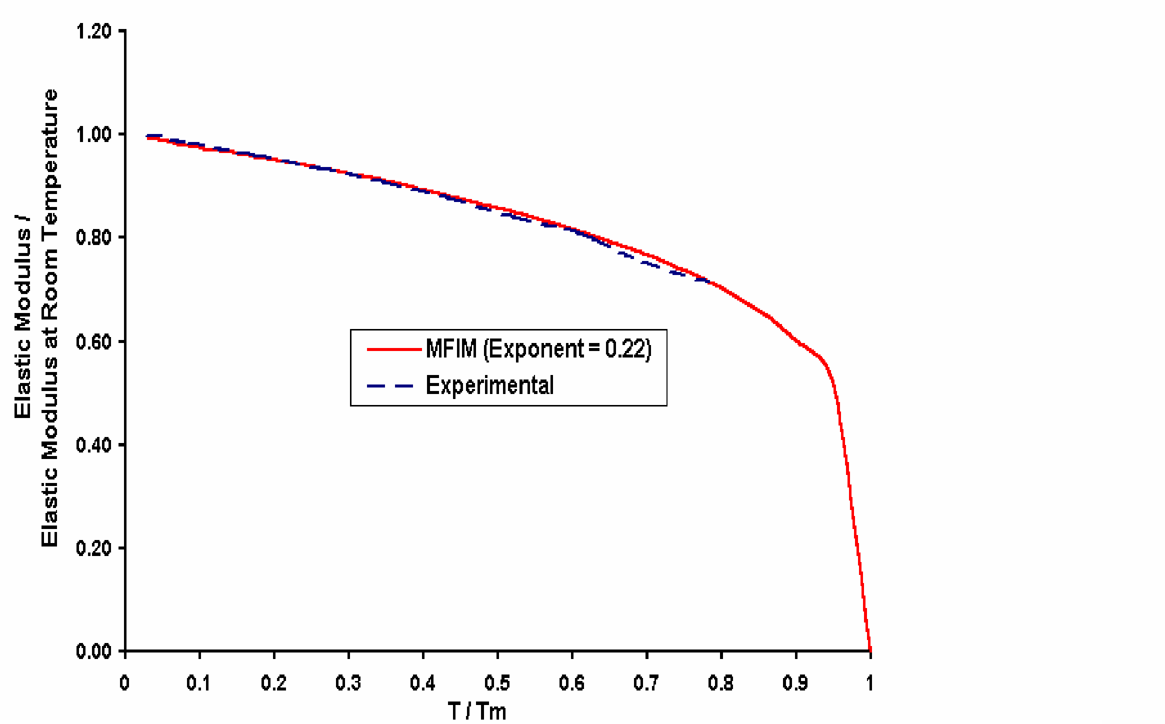

Figure 4. Effect of Temperature on Elastic Modulus of Nickel Alloy As Predicted by The Multi-Factor Interaction Model

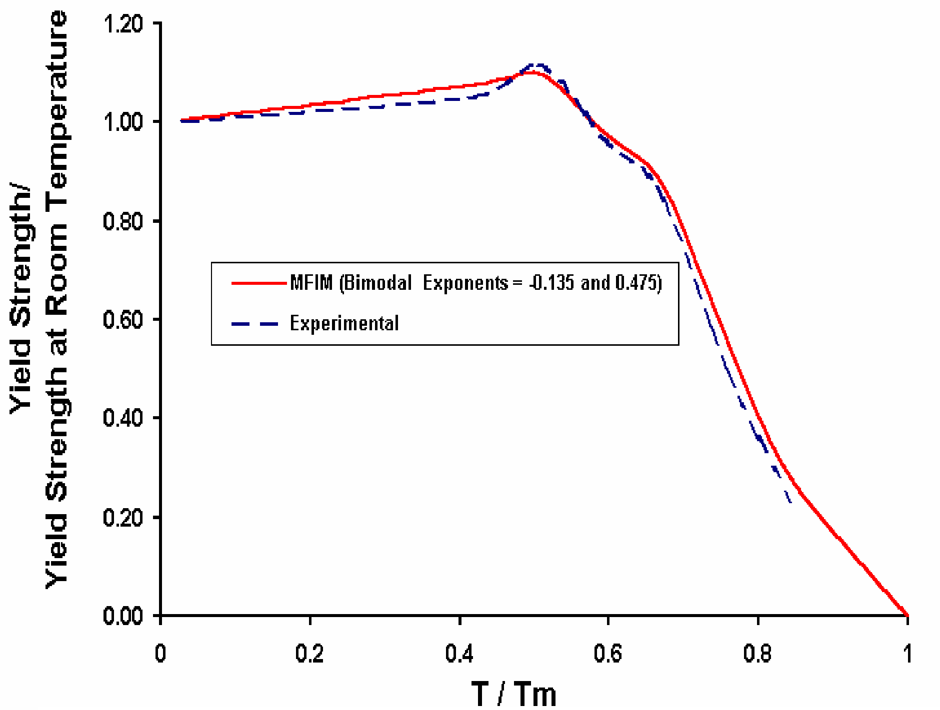

Figure 5. Effect of Temperature on Yield Strength of Nickel Alloy As Predicted by The Multi-Factor Interaction Model

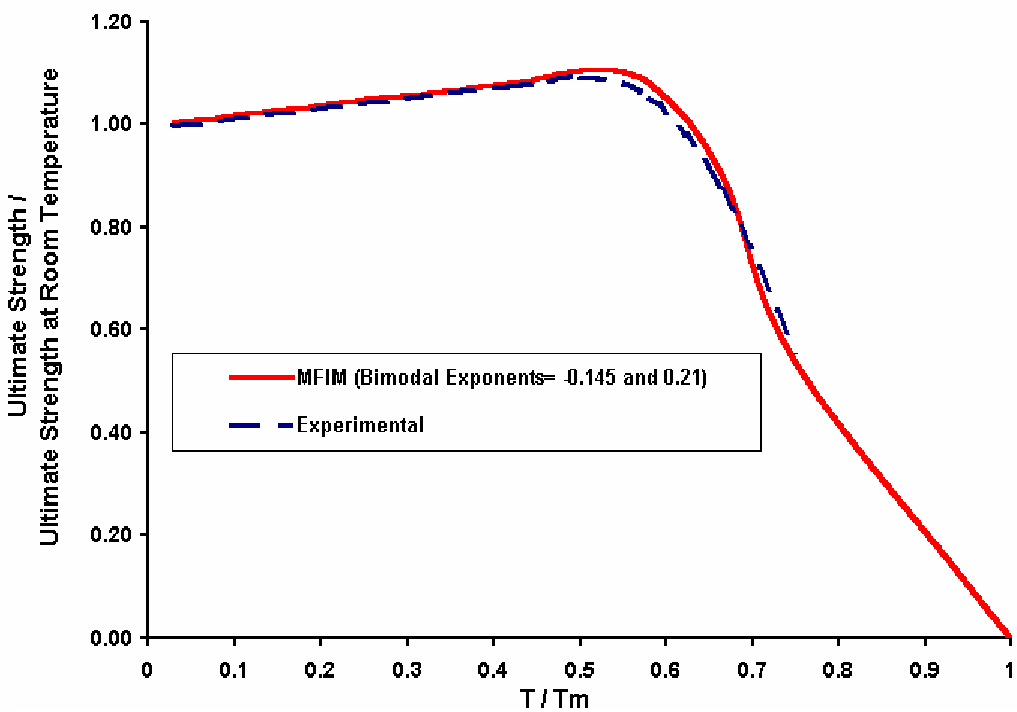

Figure 6. Effect of Temperature on Ultimate Strength of Nickel Alloy As Predicted by The Multi-Factor Interaction Model

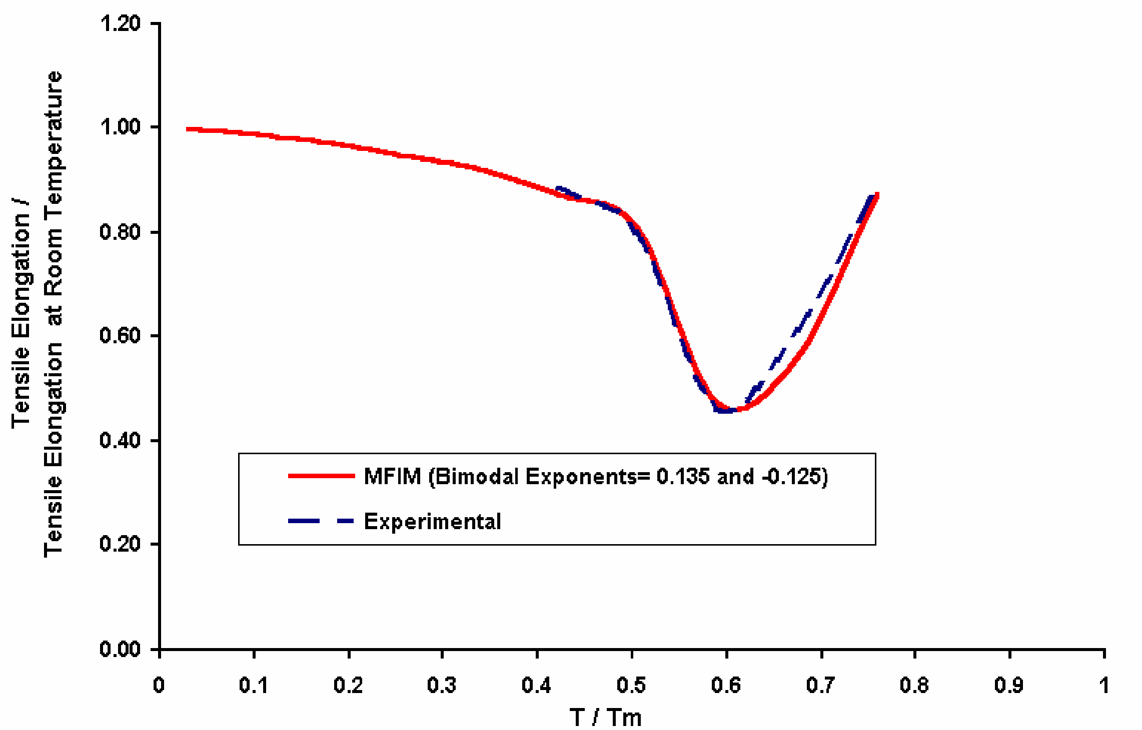

Figure 7. Effect of Temperature on Tensile Elongation of Nickel Alloy As Predicted by The Multi-Factor Interaction Model

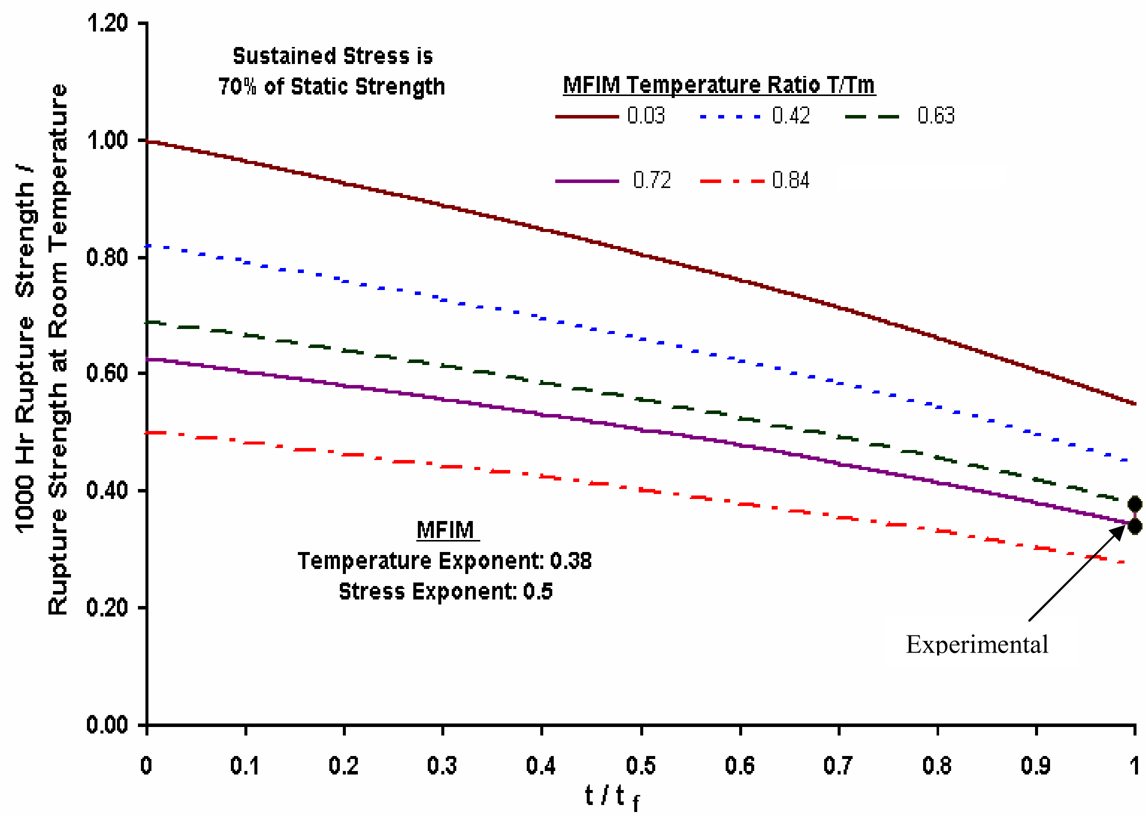

Figure 8. Effect of Temperature and Stress on the 1000 Hours Rupture Strength of Nickel Alloy As Predicted by The Multi-Factor Interaction Model

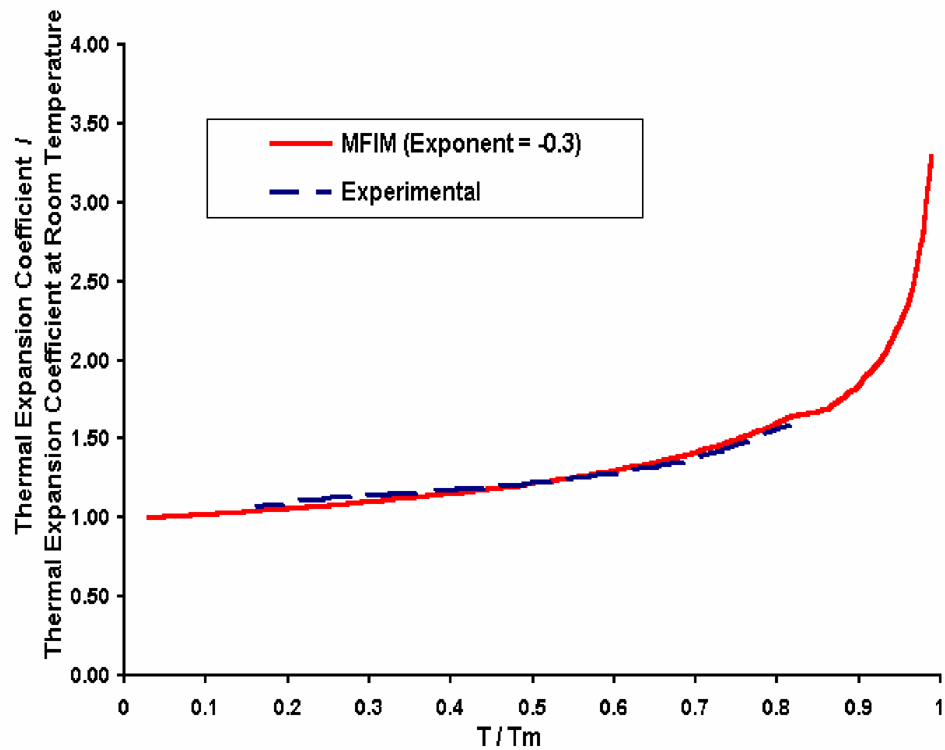

Figure 9. Effect of Temperature on the Thermal Expansion Coefficient of Nickel Alloy As Predicted by The Multi-Factor Interaction Model

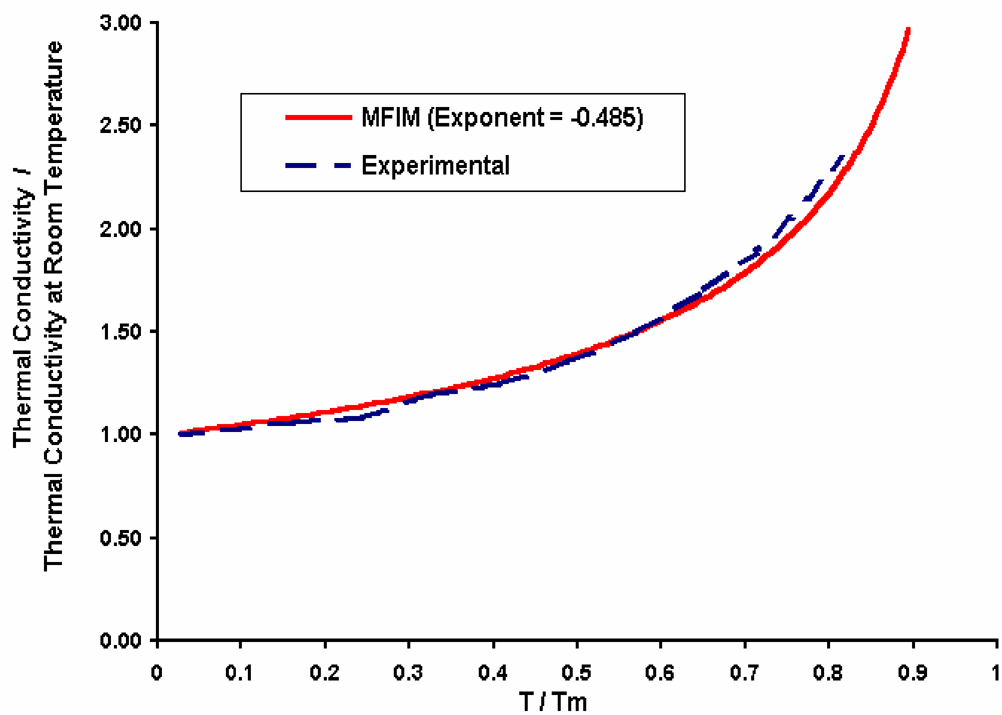

Figure 10. Effect of Temperature on the Thermal Conductivity of Nickel Alloy As Predicted by The Multi-Factor Interaction Model

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13. ABSTRACT *(Maximum 200 words)*

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